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Comparative economic analysis of gas turbine-based power generation and combined heat and power systems using biogas fuel

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A B S T R A C T

We evaluated the economic feasibility of small CHP (combined heat and power) and CC (combined cycle) systems using a 5 MW-class gas turbine fueled with biogas. The significance of this study is that we used practical hourly and seasonal variations of the CHP and CC performance based on detailed performance analysis. Using the investment and running costs of the entire facilities and the prices of electricity and heat, economic indices such as the annual gross margin, the net present value of the cash flow and the payback period were estimated. Two kinds of heat demand patterns were compared in the CHP system. Major findings are as follows. A strong dependence of the project economics on heat sales was observed. Both of the CHP cases showed an economic benefit over both the CC system and the gas turbine-only system. Another important finding is that the CHP system would be more beneficial than the CC system in terms of the total net present value after twenty years as long as the annual heat demand is over thirty percent of the annual electricity supply. The effect of increasing prices and costs was also simulated, and improvements in project economics were estimated.

1. Introduction

There is a growing need to use alternative energy sources to cope with the depletion of fossil fuel resources and the escalation of environmental concerns. Another important issue is the need to reduce greenhouse gases. In this respect, attention on the use of various kinds of biofuels in the power generation industries has grown rapidly. There are two types of gaseous biofuels. The first type of fuel is syngas, which occurs due to pyrolysis and gasification of solid wastes such as wood chips. The other fuel is biogas, which is generated from anaerobic digestion of wastes such as food wastes and animal excreta. Thus, biogas is also called digester gas. Landfill gas is a kind of biogas because its production process and composition are similar.

The use of biofuel-fired CHP (combined heat and power) systems using various kinds of prime movers is steadily increasing. GTs (gas turbines) are quite suitable for use with biofuels because of their high fuel flexibility [1]. Gas turbine CHP systems and gas/steam turbine CC (combined cycle) power plants using bio-syngas and digester/landfill gas have received considerable attention from power generation and energy industries recently. For example, studies on firing biomass in normal combined cycle [2] and integrated gasification combined cycle [3] have been published. Several cases studies on the use of biogas produced from various sites such as animal farm [4] and sewage treatment plant [5] have also been published. In addition, a possibility of constructing a trigeneration systems using biogas fired micro gas turbine [6] was researched. In particular, digester gas is suitable for small gas turbines raging from tens of kilowatts to several megawatts because the amount of digester gas produced at a single source is usually limited [6,7]. Biogas is mainly composed of CH_4 and CO_2. Since biogas contains quite a large amount of CO_2 (20–50% by volume), its heating value is quite small compared to natural gas [7]. As a result, a considerably greater quantity of biogas should be supplied to the combustor compared to the case of firing natural gas. Therefore, if the fuel is changed from natural gas to biogas, a gas turbine might produce a larger power output compared to the original natural gas fuel due to the increased turbine gas flow [7].

The evaluation of economic feasibility is quite important when considering CHP systems. Several economic analyses of CHP systems fired with natural gas, especially using gas turbines, have been published. These studies include an economic analysis that considers varying electric and thermal loads [8], an economic study that accounts for system capacity, types of prime mover, and operating scenarios [9], and an economic study that considers

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Nomenclature

C	instant cost ($)
CC	combined cycle
CF	cash flow ($)
CF_0	initial investment ($)
CHP	combined heat and power
COMB	combustor
COMP	compressor
EPC	engineering, procurement and construction
EVAP	evaporator
ECON	economizer
G	generator
GM	gross margin ($)
GT	gas turbine
HRSG	heat recovery steam generator
HX	heat exchanger
I	discount rate
IRR	internal rate of return (year)
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
N	shaft speed (rpm)
n	total project period (year)
NPV	net present value ($)
O&M	operation and maintenance
P	pressure (kPa)
PB	payback period (year)
R	gas constant (kJ/kgK)
R_{el}	electricity sales revenue ($)
R_h	heat sales revenue ($)
SMP	system marginal price ($)
ST	steam turbine
T	temperature (K)
TURB	turbine
$\dot{W}$	power (MW)
γ	specific heat ratio
η	efficiency
κ	constant

Subscripts

DG	digestion system
fs	feedstock
i	year index
in	inlet
pt	pretreatment
t	arbitrary year

different climate zones [10]. Biogas has received industrial attention as one of the important new energy sources. Thus, techno-economic analyses of biogas-fired CHP systems have been performed recently. Examples include a comparative economic analysis of different CHP systems [11], an evaluation of the economics and environmental benefits of firing biogas [12], and an application of biogas to trigeneration systems [6].

We evaluated the economic feasibility of using biogas in a small gas turbine CHP plant. The main features of this study are an economic evaluation using a detailed ambient temperature-dependent thermodynamic performance analysis; comparison of the economics of CHP and pure electricity generation systems; and an examination of the effects of varying costs and prices (which have not been simultaneously considered in previous works). A 5 MW-class gas turbine under commercial development was chosen. In order to obtain realistic economic analysis results, we performed a detailed gas turbine analysis that considered performance variation according to ambient conditions. Monthly and hourly variations in electric power generation, heat supply capacity, and fuel consumption were predicted and used for the economic analysis. We performed an economic analysis from the viewpoint of an independent power producer that sells all of the generated power to the grid, but sells heat within the limit of the demands of the consumer. For this purpose, two types of heat demand patterns were used. Using the electric power and heat production of the gas turbine, the heat demand and economic data such as plant investment costs, feedstock cost, electric and heat prices, and key economic factors such as gross margin, payback period, and net present value, were assessed. Pure electricity generation systems (the gas turbine-only and gas/steam turbine combined cycle) were also analyzed, and their economic data were compared with those of the CHP systems. The effect of varying electricity and heat prices on the system economics was also investigated.

2. System

Two types of systems were examined in this study. The first is a CHP system, as shown in Fig. 1. The GT exhaust gas generates steam, which is supplied to a heat demand site. The other system is a pure electricity generation system, as shown in Fig. 2. The steam from a HRSG (heat recovery steam generator) drives a steam turbine and recirculates in the bottoming cycle. This system is a small-scale gas/steam turbine combined cycle, and produces electricity only. The gas turbine adopted in this study is a 5 MW-class engine under development [13]. The anaerobic digestion plant converts feedstocks into raw biogas, and a fuel pretreatment system eliminates undesirable gas components in the raw biogas (such as hydrogen sulfides and siloxane), which can damage the gas turbine engine. Then, the resulting biogas is fed to a gas turbine combustor. The purpose of the separate HX (heat exchanger) is to supply heat in the form of hot water to the anaerobic digestion process. Of course, the original gas turbine was designed to burn natural gas. In this study, the fuel was switched to biogas, which we assumed to consist of 65% CH_4 and 35% CO_2 by volume. The digestion plant was not analyzed in detail, but the cost factors (equipment costs, and operation and maintenance costs) were considered. The cost and energy consumption of the pretreatment system were included. The gas turbine performance (electric power output, heat supply

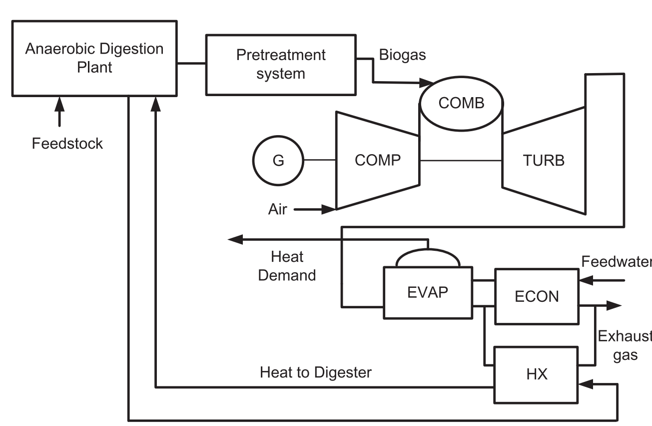

Fig. 1. Combined heat and power system configuration.